Modelling of Wind Power Plant for Voltage Regulation Simulations

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***Abstract*—The increasing penetration of renewable energy sources (RES) in networks causes the interest of distribution system operator (DSO) and transmission system operator (TSO) not only in electrical energy generation, but also in a view of voltage regulation possibilities. This article investigates voltage regulation with wind farm or wind power plant (WPP) using two approaches – modelling of each wind turbine (WT) individually and aggregation of all WTs into one. The first approach uses a detailed WPP electrical network with all WTs, cables and transformers modelled. The second approach uses a single WT connected to the WPP site and aggregates all WTs located in the actual WPP. The voltage regulation with both approaches of WPP connected to the real-life Croatian transmission system is simulated in PowerWorld Simulator. Different scenarios of consumption and voltage regulation are used in simulation. It is observed that voltage regulation with WPP is possible and from TSO point of view is negligable which model is used for voltage regulation due to the difference in voltage on the point of common coupling (PCC) being about 0.7%. From owner of WPP point of view there is question about profitability of WPP due to power losses accuring at voltage regulation.**

***Index Terms*—Wind Power Plant, Ancillary Service, Voltage Regulation, Simulation,**

I. INTRODUCTION

Along with hydroelectric power plants and photovoltaic systems, WPP are becoming the fastest-growing RES. According to [1] there is 743 GW wind power capacity worldwide. The leading countries in the production of energy from WPP are China and USA. In Europe, the leading country in energy production from WPP is Norway. According to the latest data taken from Croatian Transmission System Operator (HOPS) [2], in December 2021 there are 26 WPPs in regular operation in Croatia with a total power of 950.95 MW. In almost all WPPs there is a possibility of voltage regulation.

In traditional power systems, synchronous generators besides active power production have been used to reactive power production and voltage regulation, but in modern systems, the use of renewable energy sources for voltage regulation is becoming increasingly important. Given the type of generators and converters used, there are several types of WTs some of which can regulate voltage, and some cannot. When studying voltage regulation using WPPs, additional attention should be paid to the fact that the WPP is composed of multiple WTs. Some of the researchers in voltage regulation studies aggregate all the WTs into one thus representing the whole WPP as one big WT and some researchers model each WT individually.

In [3], an analysis of voltage regulation in the transmission network based on reactive power from WPP was performed and a conclusion was made by comparing the strategy for traditional power systems and the new strategy that includes the use of WPP for voltage regulation. To test the feasibility and effectiveness of the new strategy, it was implemented and simulated in the Hellenic power system. For the study, the authors in [3] aggregate all the WTs into one. The literature [4] deals with the problem of overvoltage due to over generation in different WPP topologies due to the operation of converter components. The WPP topologies used are radial, one-sided ring, two-sided ring, and star. The authors used DIgSILENT [5] to model each WT individually. The authors in literature [6] presented three different strategies for voltage regulation at the point of connection of the WPP with the power system and compared the advantages and disadvantages of each strategy based on the conducted simulation and analysis. In their analysis, authors in [6] used a detailed model of WPP with every WT included individually. In [7], the reactive power capability model for a WPP is presented and all the WTs are aggregated which results in a simple and easy-to-use model of a WPP. In [8], authors used WT to regulate voltage and frequency. The simulation procedure is conducted on a power network that includes different types of sources. The impact of WT on voltage and frequency regulation is tested under varied network conditions. Obtained results show that WT contributes reactive power during voltage contingencies. In [9], capacitance, inductance, and resistance are considered in WPP modeling and formulating the reactive power capability approach. Using the power capability curve of WTs, the authors proposed a voltage control strategy to meet the requirements of grid codes. To test the efficiency of the proposed method, the IEEE 33-bus system is used. The proposed strategy has provided improved performances in voltage regulation. Due to the lack of electrical data on WPPs in literature, this paper proposes a WPP test model with all necessary data for modeling. Using two approaches in modeling WPP - detailed model and aggregated which are connected on real-life transmission system, different scenarios of voltage regulation on point of common coupling (PCC) and adjacent buses are studied.

The paper is structured as follows: in Section II different WT models are presented considering their voltage regulation possibilities. In Section III, the test model of the WPP is presented with all the necessary data. Simulation implementation procedure and all scenarios are presented in Section IV and obtained results are represented in Section V. Discussion and conclusion are given in Section VI.

II. Wind Turbines and Their Voltage Regulation Possibilities

Authors in literature [10] classify WTs according to mechanical power and speed regulation. Therefore, WTs are classified to ones with:

1) fixed speed (Type 1);
2) limited variable speed (Type 2);
3) variable speed with part-scaled (Type 3);
4) variable speed with full-scaled (Type 4).

Of the 4 listed types of WTs, only Type 3 and Type 4 have the option of voltage regulation [10]. Since this paper is based on WTs which have possibility of voltage regulation, Type 3 and Type 4 will be shortly described below.

A. DFIG-based Wind Turbine (Type 3)

The configuration of WT Type 3 is consisted of slip-ring induction generator commonly known as doubly fed induction generator (DFIG). Rotor is connected to the grid via "back-to-back" converter while stator is directly connected to the grid.

Schematic diagram of WT with DFIG is shown in Fig.1 [10]. Rotor is connected via converter to the tertiary of unit transformer, while stator is directly connected to the unit transformer.

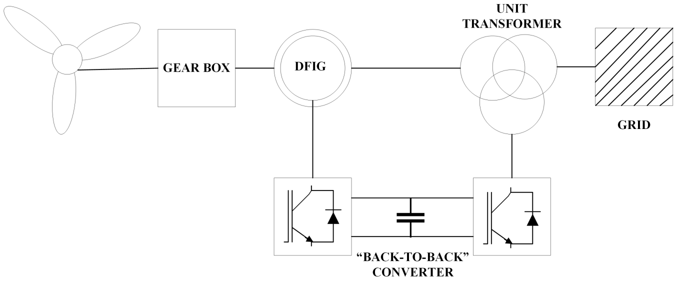

Fig. 1. WT with DFIG (Type 3) [10]

B. Full Converter Based Wind Turbine (Type 4)

WT Type 4 offers flexibility in operation due to full-scaled connection via a converter to the grid. Based on converter ability to control active and reactive power, there are no constraints in the choice of generator. Hence, the configuration of WT Type 4 may consist of the following generators: slip-ring induction generator, squirrel-cage induction generator, permanent magnet synchronous generator. Depending on the generator, the gear box can be omitted from the configuration.

Schematic diagram of WT Type 4 is shown in Fig. 2 [10]. Generator is directly connected via converter to the grid. In this case, converter can be divided into two parts: grid side converter (GSC) and machine side converter (MSC).

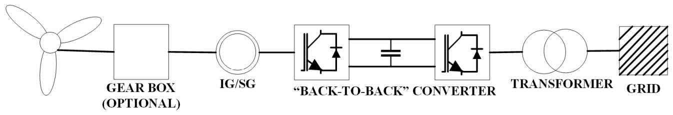

Fig. 2. Full-converter based WT (Type 4) [10]

III. Wind Power Plant Test Model

This section proposes a WPP test model that can be used for further research and testing. WPP test model is shown in Fig. 3. The model of WPP based on real-life examples consists of 23 WTs [11] with an individual power of 4.2 MW. WT is classified as WT Type 4, accordingly, full power transmission via converter is possible. WPP's maximum power is 96.6 MW. WTs are connected via TS (transformer station) 0.69/33 kV and 33 kV cables to the TS 33/110 kV which consists of two completely equal transformers of nominal power 63 MVA operating in parallel. The topology of the network is radial and consists of 5 feeders. A certain number of WT is connected to each feeder. The proposed topology is flexible and the number of feeders can be modified according to consumer needs.

Cables are chosen from [12], chosen material of conductors is aluminum and all conductors are laid horizontally. Cross section, unit resistance, unit inductance, unit capacitance, nominal current and nominal power of cables are presented in Table III.

Data of cross-section of cables and lenght of their route between buses are presented in Table VI and given in Appendix.

Except for two parallel transformers connecting the power system and WPP, each WT has its own transformer. Number of transformers, nominal power, percentage short circuit voltage and short circuit losses are presented in Table II.

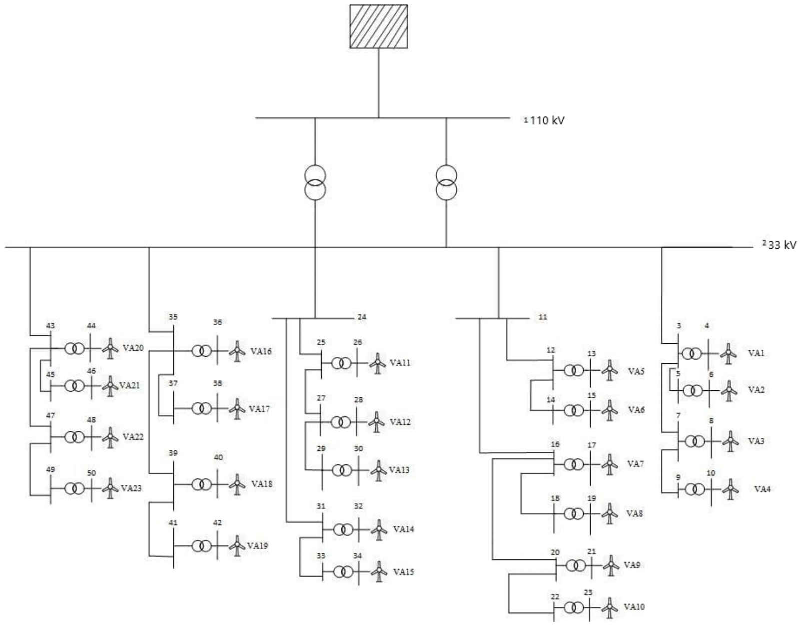

Fig. 3. WPP test model. The nominal voltage of the WPP 49-bus network is 33 kV.

TABLE I
TECHNICAL SPECIFICATIONS OF CABLES [12]

Cross-section [mm^2]	R$_1[\Omega/km]$	L$_1[mH/km]$	C$_1[\mu F/km]$	Nominal current [A]
35	0.8681	0.76	0.118	155
70	0.4432	0.69	0.144	235
120	0.2533	0.65	0.164	315
240	0.1527	0.59	0.207	458
400	0.0788	0.55	0.235	591

TABLE II
DATA OF TRANSFORMERS

Transformer	No.	Nominal power [MVA]	u$_k$[%]	P$_k[kW]$
0.69/33 kV	23	8	8	-
33/110 kV	2	63	11	150

IV. SIMULATION SCENARIOS

Voltage regulation is analyzed using two approaches in WPP electrical grid modeling - aggregation of all WTs into one (aggregated generator) and modeling of each WT individually (detailed model). The power of an aggregated is obtained by the sum of the powers of all WTs from the detailed model. WPP test model is connected to the Croatian power system model. Regarding the total production and consumption that are connected to the Croatian power system (excluding observed WPP) simulation is divided into two variants - Variant 1 where production, as well as consumption, are maximal and Variant 2 where production and consumption are minimal. Furthermore, Case A and Case C represent cases without voltage regulation in Variant 1 and Variant 2, whilst Case B and Case D represent cases with voltage regulation in Variant 1 and Variant 2. Each of the four cases is divided into two scenarios. Scenario 1 denotes that a detailed WPP model is connected to the grid in Case A and Variant 1. Scenario 2 denotes that a single generator is connected to the grid in Case A and Variant 1. Scenario 3 denotes that a detailed WPP model is connected to the grid in Case B and Variant 1. Scenario 4 denotes that a single generator is connected to the grid in Case B and Variant 1. Scenario 5 denotes that a detailed WPP model is connected to the grid in Case C and Variant 2. Scenario 6 denotes that a single generator is connected to the grid in Case C and Variant 2. Scenario 7 denotes that a detailed WPP model is connected to the grid in Case D and Variant 2. Scenario 8 denotes that a single generator is connected to the grid in Case D and Variant 2. Additional clarification of the simulation scenarios is presented in the Table III.

TABLE III
SIMULATION SCENARIOS

Case/Scenario	Voltage regulation	Detailed model/Single generator
Base Case 1	No	-
Scenario 1	No	Detailed model
Scenario 2	No	Single generator
Scenario 3	Yes	Detailed model
Scenario 4	Yes	Single generator
Base Case 2	No	-
Scenario 5	No	Detailed model
Scenario 6	No	Single generator
Scenario 7	Yes	Detailed model
Scenario 8	Yes	Single generator

Described simulation scenarios implementation procedure is shown on Fig. 4.

PowerWorld Simulator [13] software is used to model WPP as well as Croatian power system. Due to the need of software, all units are converted into a system of relative units. A base power of 100 MVA is used for the conversation. In Table IV and Table V production and consumption are shown sorted by areas, taken from PowerWorld Simulator [13]. For Variant 1, system generation and consumption increased by 40%. For

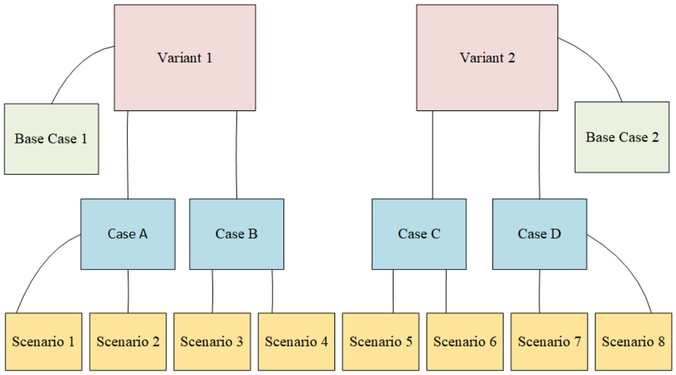

Fig. 4. Simulation implementation procedure

Variant 2, generation is reduced by reducing the generation of those power plants that are the most expensive due to fuel. Power systems are divided into areas depending on where they are located and managed by independent operators. The table also shows the exchange (import and export) of electricity with other power systems. Table IV refers to Variant 1 and Table V refers to Variant 2. A new area called the WPP was added in which the WPP losses processed in the results are shown.

TABLE IV
AREAS IN VARIANT 1

Area No.	Area Name	Generation [MW]	Load [MW]
1	Croatia	2841.32	2989.44
2	Hungary	420	
3	Slovenia	-591.58	
4	Bosnia and Herzegovina	251.29	
5	Serbia	150.06	

TABLE V
AREAS IN VARIANT 2

Area No.	Area Name	Generation [MW]	Load [MW]
1	Croatia	1821.11	1793.61
2	Hungary	420	
3	Slovenia	-586.83	
4	Bosnia and Herzegovina	256.04	
5	Serbia	158.64	

V. RESULTS

The results of simulation scenarios are presented below. Bus Number 1 presents a PCC, Bus Number 2 and 3 presents adjacent buses.

A. *Results for Variant 1*

A comparison of voltages on the PCC and adjacent buses of Base Case 1, Scenario 1 and Scenario 2 belonging to Case A in which voltage regulation is off is shown in Fig. 5. Regardless of the model, there is an increase in voltage on all three buses in Scenario 1 and Scenario 2 compared to Base Case 1. In Scenario 1 there is the lower voltage on buses compared to Scenario 2. The reason for that is voltage drop which occurs in the WPP grid itself and that does not exist in the aggregated model.

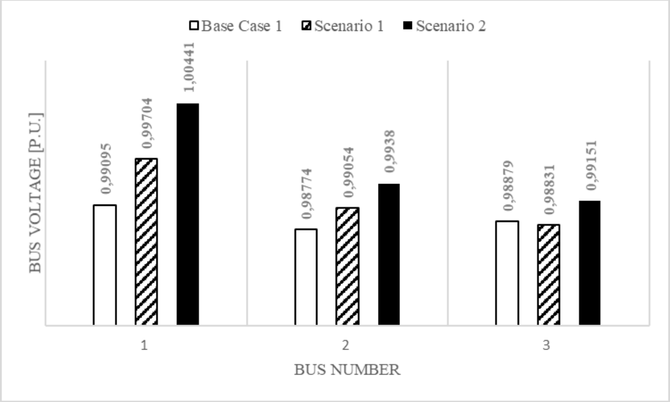

Fig. 5. A comparison of voltages on the connection bus and adjacent buses of Base Base 1, Scenario 1 and Scenario 2

A comparison of voltages on the PCC and adjacent buses of Base Case 1, Scenario 3, and Scenario 4 belonging to Case B in which voltage regulation is on is shown in Fig.6. The set value of the voltage regulator is 1.05 p.u. The bus voltages have increased according to the set value compared to the previous case and it can be concluded that the voltage regulation brings significant results. Like in previous case, voltages are higher when the aggregated model of WPP supplies the grid. The voltages on PCC of Scenario 3 and Scenario 4 differ in the second decimal place or 0.69%, which is negligible from the point of view of the system operator.

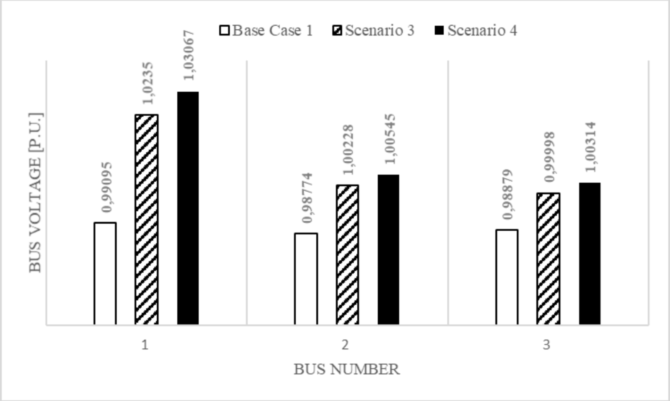

Fig. 6. A comparison of voltages on the connection bus and adjacent buses of Base Base 1, Scenario 3 and Scenario 4

B. *Results for Variant 2*

A comparison of voltages on the PCC and adjacent buses of Base Case 2, Scenario 5, and Scenario 6 belonging to Case C in which voltage regulation is off is shown in Fig.7. Bus voltages are higher in Variant 2 than bus voltages in Variant 1. In both models, voltages are higher compared to Base Case 2. Due to voltage drops in the detailed model of WPP, which have an impact on bus voltages, in the aggregated model there is a higher bus voltage.

A comparison of voltages on the PCC and adjacent buses of Base Case 2, Scenario 7, and Scenario 8 belonging to Case

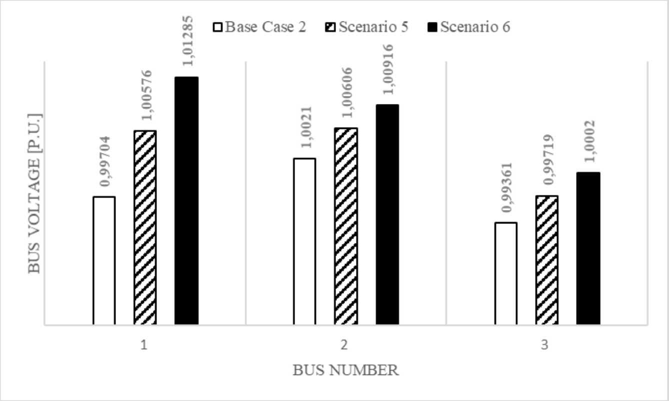

Fig. 7. A comparison of voltages on the connection bus and adjacent buses of Base Base 2, Scenario 5 and Scenario 6

D in which voltage regulation is on is shown in Fig.8. The set value of voltage regulator is 1.05 p.u. Voltages tend to set value more than Variant 1. Voltages in Scenario 7 i Scenario 8 on PCC differs at the third decimal place or 0.67%.

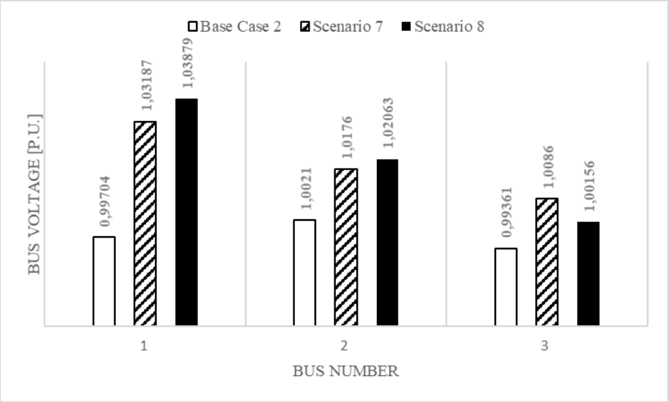

Fig. 8. A comparison of voltages on the connection bus and adjacent buses of Base Base 2, Scenario 7 and Scenario 8

C. Power Losses in a Detailed WPP Grid

Losses in detailed WPP grid in Variant 1 and Variant 2 are represented in Fig. 9 and Fig. 10. In both variants losses are higher when voltage is regulated. During voltage regulation WPP injects reactive power in the grid. Reactive current contributes to the total current. Since losses depend on the square of the current, there is an increase in losses when regulating the voltage.

VI. CONCLUSION

This paper aims to make a detailed model of the WPP grid. The second aim of this paper was to investigate the impact of a detailed and aggregated model of WPP on voltage regulation. Concluding remarks can be made from two different points of view - from the point of view of the power system operator and the point of view of the owner of WPP. The negligible difference (0.69% for Variant 1 and 0.67% for Variant 2) in obtained results between voltages magnitude on PCC suggests that in this case aggregated model would be used. The question arises about the profitability of the WPP due to increased losses in the WPP network during voltage regulation. One of the possible solutions to the losses is to create an agreement between the power system operator and the VPP owner in the form of monetary compensation for voltage regulation. Future research might aggregate all impedances and admittances of cables and transformers in WPP grid and that model test for voltage regulation and compare with afromentioned approaches.

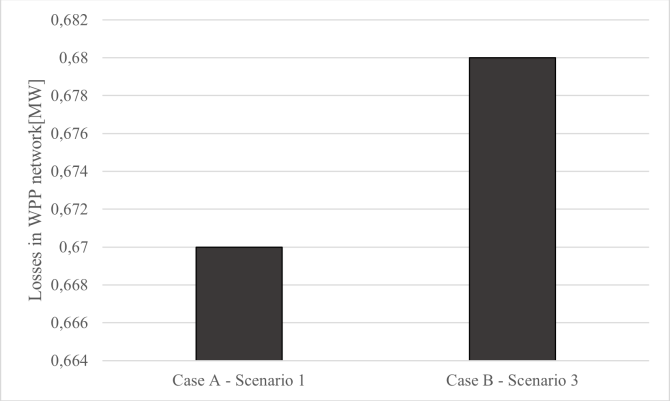

Fig. 9. Power losses in detailed WPP in Variant 1

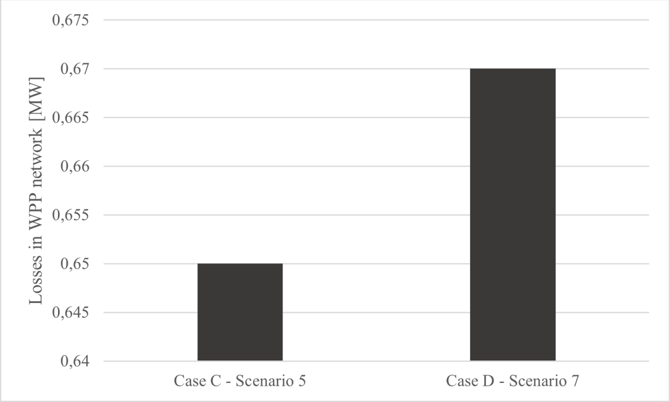

Fig. 10. Power losses in detailed WPP in Variant 2

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APPENDIX

Table VI presents data of cross-section of cables and lenght of their route between buses.

TABLE VI
DATA OF CABLES BETWEEN BUSES

From bus to bus	Cross-section [mm^2]	Lenght of route [m]
2-3	240	2500
3-5	35	650
3-7	70	1450
7-9	35	450
2-11	400	1350
11-12	70	600
11-16	240	1600
12-14	35	500
16-18	35	480
16-20	70	1200
20-22	35	900
2-24	240	1200
24-25	120	200
24-31	70	1450
25-27	70	530
27-29	35	600
31-33	35	1050
2-35	240	1200
35-37	35	1500
35-39	70	470
39-41	35	500
2-43	240	2900
43-45	35	630
43-47	70	1500
47-49	35	540